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Experimental assessment of the effect of wearing hearing protectors on the audibility of railway warning signals for normal hearing and hearing impaired listeners

--Manuscript Draft--

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Abstract:	<p>The influence of wearing hearing protectors on the detection of seven railway warning signals in noise was evaluated by comparisons of the masked thresholds measured with and without hearing protectors, out of a total of eighty listeners. The results show that wearing the HPDs improves the audibility for normal hearing listeners whereas it tends to impede the audibility for hearing impaired listeners. Moreover, the impediments greatly depend on the warning signal acoustical characteristics.</p> <p>Statistical analyses were performed in order to propose a criterion for hearing impaired listeners that guarantees their security when wearing hearing protectors. If we do not consider one given high-pitched signal that is not suitable as a warning signal, the conclusion is that the security is assured when the average absolute hearing threshold (average at 500, 1000 and 2000 Hz on the best ear) of the listeners remains lower than 30 dB Hearing Level.</p>

Experimental assessment of the effect of wearing hearing protectors on the audibility of railway warning signals for normal hearing and hearing impaired listeners

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1. Introduction

In noisy workplaces, acoustic warning signals are often used to promptly alert workers of a dangerous situation. To guarantee the workers' safety, the audibility of warning signals is of paramount importance. This audibility can however be impeded in practice by the wearing of hearing protection devices (HPDs), especially for hearing impaired workers [1].

Nevertheless, according to Directive 2003/10/EC [2], HPDs should be worn when **A-weighted** daily noise exposure levels exceed 80 dB to avoid hearing impairment and, over 85 dB, this becomes strictly imperative.

In a previous study [3], the effect of wearing HPDs on the audibility of railroad warning signals was evaluated on normal hearing (NH) listeners from masked threshold measurements performed both with and without wearing the HPDs. The results of this former study evidenced that wearing the HPDs generally improved the audibility (as compared to no HPD) for warning signals having a sufficient amount of energy in the low-frequency range ($f < 1500$ Hz). On the contrary, for hearing-impaired (HI) listeners, other previous studies suggest that HPDs can have a more detrimental effect [4, 5, 6, 7]. This is probably due to a joint effect of elevated absolute thresholds and broadened auditory filters. This result remains to be confirmed with some specific warning signals and the present study was therefore dedicated to evaluate the effect of wearing HPDs on the detection of railroad warning signals for both NH and HI listeners.

2. Expected effects of wearing HPDs

The influence of wearing HPDs on the audibility of a warning signal is traditionally assessed by evaluating the masked detection threshold of the signal both with and without wearing the HPD [6]. The masked detection threshold is defined as the sound level of a signal at which this signal embedded in noise is just detectable. When the masked detection threshold with the HPD is smaller (respectively larger) than the masked threshold without the HPD, wearing the HPD improves (respectively impedes) the audibility of the signal.

As described in the literature, two phenomena may explain an impediment of the audibility when wearing HPDs; while a third phenomenon could explain an improvement of the audibility [3, 6].

First, detection may be impeded because the sound attenuation provided by the HPD leads the warning signal levels to be below the absolute thresholds of the workers; so that the signal cannot be heard anymore [4]. For normal hearing workers, this over-protection effect might only appear for low to moderate noise levels in which the wearing of HPDs is not required. However, for hearing impaired workers, this over-protection effect may extend to much higher levels, especially in high frequency bands where

51 absolute thresholds are usually higher [8, 9] and HPD sound attenuations are usually
52 also larger.

53

54 Second, detection may be impeded by an increase of the upward spread of masking [4]
55 when the HPD is worn. An increase of the upward spread of masking mostly happens
56 when a low-frequency noise is combined with a HPD having smaller sound attenuation
57 values in the low frequency range than in the high-frequency range (which is the case
58 for most HPDs). In such a configuration, the masking of the higher frequency bands by
59 the lower frequency bands is only slightly modified by the HPD due to its rather reduced
60 sound attenuation values in the low frequency range. Moreover, the high-frequency
61 components of the warning signal are strongly attenuated by the HPD and the potential
62 masking effect of the noise is enhanced accordingly. Since HI listeners usually exhibit
63 broadened auditory filters [10, 11, 12], their upward spread of masking is increased
64 compared to NH listeners. This could then contribute to a larger detrimental effect of the
65 HPDs on the audibility for HI listeners. To avoid this detrimental effect, Standard No. EN
66 458:2016 [13] recommends the use of HPDs with ‘flat/uniform’ sound attenuation,
67 defined as HPDs with high frequency (H) minus low-frequency (L) sound attenuation
68 values less than or equal to 9 dB. This recommendation of ‘flat/uniform’ attenuation might
69 be particularly important for HI listeners because they are more affected by steeply
70 sloped attenuation functions than NH listeners [4]. For example, Giguère and Berger [4]
71 suggested that the attenuation slope should not exceed 6-7 dB/octave for mild hearing
72 loss and 3-4 dB/octave for moderate to severe high frequency hearing loss in order to
73 minimize the adverse effects of HPDs on the speech frequency range.

74 Besides, as part of the German criteria proposed by Liedtke in 2009 [14], the AIP
75 criterion¹ states that a HPD is suitable when the slope of the linear regression of mean
76 values of sound attenuation (obtained according to Standard No. ISO 4869-1:2018 [15])
77 for 125–4000 Hz is less than 3.6 dB/octave.

78

79 Third, HPDs can also improve the detection of warning signals in noise [6]. This
80 improvement would then be related to the non-linear growth of masking effects when
81 noise levels increase (see Moore [16] and Moore’s method in Standard No. ANSI
82 S3.4:2007 [17]). When wearing a HPD, the reduced noise levels at the ear increase
83 frequency selectivity (sharpened auditory filters) and consequently reduce masking,
84 resulting in lower masked thresholds [6].

85

86 Even though these three phenomena are well described in the literature, the influence of
87 wearing HPDs appears to depend on several factors such as the relative spectral
88 distributions of the noise and the warning signal, the sound attenuation of the HPD and
89 the hearing status of the subjects (both absolute thresholds and frequency selectivity).
90 Altogether, this makes the effect of wearing HPDs unpredictable and the experimental
91 results may sometimes appear contradictory (see, Lazarus [5] for an extensive review).

92 **3. Objective and methods**

93 The aim of this study was then to evaluate the effect of wearing HPDs on the audibility
94 of railroad warning signals for both NH and HI listeners. The methods involved three
95 main steps: (1) the choice of the warning signals and background noises to be tested,
96 (2) the measurement of the masked thresholds with and without HPDs and (3) the choice
97 of the statistical tests used to compare the masked thresholds with and without HPDs.

1 AIP stands for “Audibility, speech Intelligibility or Perception of informative operating
sound ”

98 These three steps are further detailed in the next three sections. Next, from the results
99 of the statistical analyses, a criterion based on the absolute thresholds is then proposed
100 in order to guarantee the security of HI workers when wearing HPDs.
101

102 **3.1. Warning signals and background noises**

103 To better match a realistic configuration, all the warning signals and background noises
104 used in the experiment were recorded in the field, close to the ears of a worker located
105 at his usual working area. Time recordings were performed using a calibrated class 1
106 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of
107 48 kHz. Seven warning signals daily used in the French railroad environment were
108 tested. They were chosen among others to get a diversity of time and frequency
109 characteristics (see Table 1). All but one have a harmonic structure (i.e., they are
110 composed of a fundamental frequency f_0 and of multiples of f_0). On the contrary, the
111 remaining RS signal is composed of two pure tones with no harmonic relationship.
112 All but two (DAPR and GSM) signals are stationary. DAPR and GSM consisted in an
113 alternation of two tones with high and low fundamental frequencies (see Table 1). The
114 first four signals in Table 1 are used to warn track workers from an incoming train. The
115 last three signals are used to inform train drivers of an event and require an action from
116 them (like pressing or releasing a driving component).

117
118 Table 1: Temporal and spectral characteristics of the warning signals.
119

120
121 All track workers' signals were tested in a ballast plough background noise whereas all
122 train drivers' signals were tested in the background noise generated by a railway vehicle
123 at maximal speed. The third-octave spectra of both background noises are shown in
124 Figure 1. These two background noises were chosen because much of their energy is
125 distributed in the low-frequency range ($f < 1000$ Hz). Such noises should then have a
126 larger potential masking effect [5].
127

128
129 Figure 1: Third-octave band spectra of background noises. Ballast plough noise (—);
130 railway vehicle noise (----).
131

132 **3.2. Masked threshold measurements**

133 The masked thresholds were measured using a two-interval, two-alternative forced
134 choice (2I-2AFC) procedure. The sound intervals (one containing only the background
135 noise, the other containing both the background noise and the warning signal) were
136 successively presented in random order. The listener's task was then to indicate the
137 interval with the warning signal. Each interval consisted in a 500 ms burst of noise and
138 the two intervals were separated by a 300 ms silent gap. The warning signal was 300
139 ms long and was temporally centered in the middle of one burst of noise (i.e. in the middle
140 of one interval). The A-weighted background noises level was constant and equal to 86
141 dB. At the beginning of the measurement procedure, the A-weighted level of the warning
142 signals was also set at 86 dB. This level varied during the measurement procedure
143 according to a "2 Down – 1 Up" adaptive rule to target a detection threshold
144 corresponding to 70.7% of detection [18]. The level of the signal first varied by steps of
145 5 dB. After three reversals, the variation step was reduced to 3 dB. After two additional
146 reversals, the step reached its final value of 1 dB. Once the last step of 1 dB was reached,

147 the test continued until four additional reversals were obtained. The masked threshold
148 value was then computed as the mean of these four last reversals.
149

150 **3.3. Statistical analyses**

151 The listeners were grouped in five different hearing classes depending on their absolute
152 thresholds values. From the measured masked thresholds obtained for each hearing
153 class and each HPD configuration (no HPD, earplugs, earmuffs), Shapiro–Wilk tests [19]
154 were first performed to evaluate the normality of the threshold distributions. Since the
155 normality assumption was not always true (i.e. $p < 0.1$), Wilcoxon rank tests [20] were
156 therefore performed (instead of Student's t tests which require a normal distribution of
157 the data) to compare the masked thresholds of HI listeners with those of NH listeners.
158 Next, Wilcoxon matched-pairs signed-rank tests were applied for each hearing class
159 upon the differences between protected and unprotected thresholds in order to better
160 characterize the beneficial or detrimental effect of HPD upon detection.

161 **4. Psychoacoustic experiments**

162 **4.1. Experimental set-up**

163 The psychoacoustic tests took place in a sound-proof room (rough dimensions $w \times d \times h =$
164 $5.4 \text{ m} \times 5.9 \text{ m} \times 2.9 \text{ m}$) treated in absorption (reverberation time of 0.42 s).
165 The listener was sat 2.6 m in front of one loudspeaker (KH 120A by Neumann, Germany)
166 that played the warning signals. The background noises were played by two other
167 loudspeakers (LSR6332 by JBL, USA) driven by a power amplifier (XLS 402 by Crown,
168 USA). The positions and orientations of these two loudspeakers were experimentally
169 determined to get a uniform sound field around the listener's head.
170 The uniformity of the sound field has been accurately controlled with acoustic
171 measurements performed at the center of an anticipated head and at six positions
172 situated 15 cm from the center (right, left, front, rear, up, down). The discrepancies
173 between each of these six positions and the center, for the two background noises used
174 in the experiment (played by the two LSR6332 speakers) and for a pink noise played on
175 the KH 120A loudspeaker, never exceeded 3 dB in 1/3 octave bands from 80 to 12500
176 Hz.
177 All audio signals were calibrated before each test session with a microphone located at
178 the same position than the center of the participant's head. The calibration consisted of
179 adjusting the gain of each audio signal (background noises and warning signals) to set
180 the **A-weighted** background noise level and the **A-weighted** warning signal level equal to
181 86 dB.
182

183 **4.2. Subjects**

184 Before their participation, subjects were first informed of the types of tests they were
185 going to take part in and of the anonymization process of the collected data. They were
186 then offered the opportunity to provide their informed consent.
187 Eighty people (25 females, 55 males) aged from 18 to 81 (mean 51.6 years, standard
188 deviation 15.3 years) participated to the experiment. Fifty-three people were SNCF
189 workers who volunteered to take part into the experiment during work-time. Twenty-
190 seven additional participants were recruited and paid a hourly-wage for their
191 participation. The participants' absolute hearing thresholds were measured performing a
192 pure-tone audiometry at the 11 standard audiometric frequencies from 125 to 8000 Hz

(see Figure 2). The participants were then distributed into five different hearing classes according to their absolute thresholds. The participants from the first class were considered as normal hearing (NH) listeners and had absolute thresholds below 20 dB hearing level (HL) from 125 to 8000 Hz on both ears. Eighteen participants were considered as NH listeners. The remaining participants were distributed into four additional classes depending of their average absolute threshold at 500, 1000 and 2000 Hz on the best ear, noted PTA (for Pure-Tone Average) hereafter **and expressed in hearing level dB**. Four classes of hearing impaired (HI) listeners were then considered:

- HI1: $10 < \text{PTA} \leq 20$ dB, 22 listeners
- HI2: $20 < \text{PTA} \leq 30$ dB, 18 listeners
- HI3: $30 < \text{PTA} \leq 40$ dB, 14 listeners
- HI4: $\text{PTA} > 40$ dB, 8 listeners.

Figure 2: Mean absolute thresholds of the five hearing classes (**expressed in hearing level dB**). From top to bottom: NH (\cdot); HI1 (\circ); HI2 ($*$); HI3 ($+$); HI4 (\times).

Figure 2 shows the mean absolute thresholds of the five hearing classes. Additionally, Table 2 provides the mean ages for each hearing class. For the HI classes, the increase of absolute thresholds as a function of frequency is typical of age-related hearing loss [8].

Table 2: Mean ages and *SD* for the 5 hearing classes

4.3. Hearing protectors

Two types of passive HPDs were tested:

- Earplugs: silicon custom-molded earplugs from ELACIN, France (model Clearsound with an RC15 acoustic filter, single number rating (SNR) =17 dB)
- Earmuffs from Howard Leight by Honeywell (model Clarity C1, SNR = 25 dB).

Figure 3 shows the sound attenuation values provided by the manufacturers according to Standard No. ISO 4869-1:2018 [15]. These two HPD models were chosen because their sound attenuation profiles are relatively uniform as a function of frequency. The slope of the linear regression of mean values of sound attenuation from 125 up to 4000 Hz is of 2.7 dB/oct for the earplugs and of 1.9 dB/oct for the earmuffs. As a consequence, both HPDs fulfill the AIP criterion proposed by Liedtke [14] (with a slope lower than 3.60 dB/octave) along with the recommendation by Giguère and Berger [4] for moderate to severe high frequency hearing loss (with a slope lower than 3-4 dB/octave).

Figure 3: Mean sound attenuation values provided by the manufacturers for the two HPDs. Note: Error bars designate + 1 *SD* (earplugs) and – 1 *SD* (earmuffs).

4.4. Test procedure

For masked threshold measurements, listeners were first asked to listen to the 7 warning signals alone (i.e. without any background noise). They were then trained on how to put on the HPDs and performed at least three masked threshold measurements for practice. The presentation order of experimental conditions (combination of warning signals and HPDs configurations) was randomized for each listener. Each condition was repeated three times and the three masked thresholds values were then averaged. However, if

244 the standard deviation of the masked thresholds on these three measurements
245 exceeded 3 dB, a fourth measurement was performed and the threshold was computed
246 as the average of the three nearest values. Thus each listener performed a minimum of
247 63 threshold measurements (7 alarms × 3 configurations of HPD × 3 repetitions)
248 distributed into 6 sessions of 10 or 11 measurements (the 6 sessions were distributed on
249 several days). The duration of one session typically varied between 20 and 30 minutes
250 leading to about 2,5 hours of testing for each participant.

251 **5. Results and discussion**

252 **5.1. Masked thresholds measurements**

253 Figure 4 shows the masked thresholds without HPD, plot as box and
254 whisker², independently for the five hearing classes and for the 7 warning signals. It
255 appears that the differences on the medians between the HI classes and the NH class
256 never exceed 10 dB and the difference of the medians between HI4 and NH averaged
257 across alarms is equal to 4.9 dB. Moreover, these differences greatly depend on the
258 warning signal considered.

259 Wilcoxon rank-sum tests for unmatched data were applied to these results in order to
260 estimate the effect of hearing impairment. The results of these statistical analyses,
261 presented in Table 3, indicate no significant differences ($p > 0.05$) between the HI classes
262 and the NH class for the signals AUTOPROVA and RS; whereas the differences are
263 significant ($p < 0.05$) between at least one HI class and the NH class for the five other
264 signals.

265
266
267 Figure 4: Masked thresholds without HPDs for the seven warning signals. For each
268 warning signal, the five box and whisker plots correspond to the five hearing classes
269 considered, from the NH class most to the left to the HI4 class most to the right.

270
271
272 Table 3: Masked threshold without HPDs (see Figure 4). Statistical results (p) of the
273 comparisons between the HI classes and the NH class. Values in bold, italic and with
274 the “*” sign indicate a statistically significant difference ($p < 0.05$).

275
276
277 Figures 5 and 6 show the masked thresholds with HPDs independently for the five
278 hearing classes and for the 7 warning signals. Figure 5 shows the results with the
279 earplugs and Figure 6 with the earmuffs.

280 The differences on the medians between the HI4 and the NH averaged across alarms
281 are respectively 10.1 dB and 11 dB for the earplugs and the earmuffs. Hence, these
282 differences are larger than the average difference without HPDs (4.9 dB).

283
284 This larger effect of hearing impairment when wearing HPDs is confirmed by the results
285 of the statistical analysis (Wilcoxon rank-sum tests for unmatched data) presented in
286 Table 4. In fact, significant effects of hearing impairment are found for all but one warning
287 signal (VACMA). For all the other warning signals, some HI groups have significant

2 On each box, the central mark indicates the median, and the bottom and top edges of the box (of numerical values q_1 and q_3 , respectively) indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. The data points are drawn as outliers if they are greater than $q_3 + 1.5 \times (q_3 - q_1)$ or less than $q_1 - 1.5 \times (q_3 - q_1)$.

288 higher thresholds than the NH group. Moreover, it seems from Table 4 that the effect of
289 hearing impairment increases when increasing the degree of hearing loss. Except for the
290 VACMA warning signal, the detection performances of the HI3 and HI4 groups are
291 always significantly poorer than for the NH group. Besides, the significance of the
292 differences between HI and NH listeners are very similar for the two HPDs considered
293 (earplugs and earmuffs).

294
295
296 Figure 5: Masked thresholds with earplugs for the seven warning signals. For each
297 warning signal, the five box and whisker plots correspond to the five hearing classes
298 considered, from the NH class most to the left to the HI4 class most to the right.
299

300
301 Figure 6: Masked thresholds with earmuffs for the seven warning signals. For each
302 warning signal, the five box and whisker plots correspond to the five hearing classes
303 considered, from the NH class most to the left to the HI4 class most to the right.
304

305 Table 4: Masked threshold with earplugs and earmuffs (see Figures 5 and 6). Statistical
306 results (p) of the comparisons between the HI classes and the NH class. Values in
307 bold, italic and with the “*” sign indicate a statistically significant difference ($p < 0.05$).
308
309

310 In summary, when no HPDs are worn, the differences between the masked thresholds
311 of the HI classes and those of the NH class are relatively small and are statistically
312 significant only for 4 out of the 7 signals tested. With HPDs, the differences between HI
313 and NH increase and become significant for all the warning signals except the VACMA
314 signal. The reason why there is no difference between HI and NH for the VACMA signal
315 is most certainly due to the fact that its audibility is governed by a dominant component
316 in low-frequency ($f_0=334$ Hz) that is not or little affected by the two phenomena leading
317 to an impediment of the detection (see section 2). Moreover, both HPDs (earplugs and
318 earmuffs) lead to the same pattern of results.
319

320 **5.2. Differences between protected and unprotected thresholds**

321 To better evaluate the effect of wearing HPDs on the detection of warning signals, the
322 differences between protected and unprotected thresholds have been computed. A
323 positive difference value indicates that the HPD impedes the detection (as compared to
324 no HPD); conversely a negative value corresponds to an improvement of the detection.
325 Figures 7 and 8 show these differences for the earplugs and the earmuffs, respectively.
326
327
328

329 Figure 7: Differences between thresholds with and without earplugs for the seven
330 warning signals. For each warning signal, the five box and whisker plots correspond to
331 the five hearing classes considered, from the NH class most to the left to the HI4 class
332 most to the right.
333
334

335 Figure 8: Differences between thresholds with and without earmuffs for the seven
336 warning signals. For each warning signal, the five box and whisker plots correspond to
337 the five hearing classes considered, from the NH class most to the left to the HI4 class
338 most to the right.
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Additionally, Wilcoxon matched-pairs signed-rank tests were performed to evaluate whether these differences were statistically positive or negative. Table 5 summarizes the statistical results: an up arrow symbol³ “↑” designates a statistically significant impediment ($p < 0.05$); a down arrow symbol “↓” symbol designates a statistically significant improvement ($p < 0.05$) and no symbol designates no statistically significant effect.

Table 5: Differences between protected and unprotected thresholds (see Figures 7 and 8). Statistical results of the significant improvements (“↓” symbol, $p < 0.05$) or impediments (“↑” symbol, $p < 0.05$). No symbol indicates no statistically significant difference ($p > 0.05$).

For NH listeners, it appears that wearing any of the two HPDs improves the detection for all the warning signals (except VACMA). These improvements for NH listeners are consistent with the results from previous studies [3, 5, 21]. For the VACMA signal, most of the audibility is due to a dominant component in low-frequency ($f_0=334$ Hz). It can then be hypothesized that no improvement is found due to the reduced attenuation values of the HPDs around 300 Hz (which lead, as compared to no HPD, to a low reduction of the frequency masking phenomena, see section 2).

For HI listeners, detection improves for less and less warning signals when the absolute thresholds (i.e. the hearing loss) increase. As such, for the HI1 class, detection is improved for both HPDs for three warning signals (DAPR, STDIZIER and GSM), whereas for the HI3 and HI4 classes, no statistically significant improvement is found whatever the warning signal and the HPD considered.

Concerning the impediments, the RS warning signal is by far the most impeded signal: the differences between protected and unprotected thresholds reach around 10 dB on the medians for the HI4 class and statistically significant differences are found for HI2, HI3 and HI4 classes for earplugs and for all the HI classes for the earmuffs. This severe impediment is most certainly due to the fact that the RS signal is made of two high-frequency components (3430 and 4084 Hz). Indeed, over 3 kHz, both the absolute thresholds values and the HPD attenuations are high (see Figures 2 and 3), leading to an over-attenuation effect due to the absolute thresholds (as described in [4], see section 2). This signal is not in agreement with Standard No. ISO 7731:2003 [22], which recommends to use two dominant components between 500 and 1500 Hz and highlights that, when people wear HPDs or suffer from hearing loss, the signal must have enough energy below 1500 Hz. This signals should therefore be modified to increase its energy in the low-frequency range ($f < 1500$ Hz) to be better detected.

Significant impediments are also found with earplugs for the warning signal GSM (HI4) and with earmuffs for the warning signal AIGU for HI3 and HI4 classes.

It is worth noting that no statistically significant impediment is found whatever the hearing class considered for the four remaining warning signals: PROVA, DAPR, STDIZIER and VACMA. This can be explained by the fact that these signals have a dominant fundamental frequency in low-frequency (between 334 and 660 Hz, see Table 1) that is not or little affected neither by the absolute thresholds effect nor by the upward spread of masking effect (see section 2). Hence these warning signals appear to be particularly adapted to HI listeners.

³ The *up* arrow was chosen to indicate a threshold *elevation* when HPDs are worn (as compared to no HPD)

391 **5.3. Towards a criterion for HI listeners wearing HPDs**

392 The previous section has shown that wearing the HPDs improves the audibility for NH
393 listeners whereas it tends to impede the audibility for HI listeners. Moreover, the
394 impediments greatly depend on the signal considered.

395 In an attempt to propose a criterion based on the absolute thresholds of HI people that
396 guarantees their security when wearing HPDs, two approaches have been used.

397 In the first approach, it was simply considered that any significant impediment should be
398 avoided. From Table 5, the security of all HI classes could not be guaranteed because
399 of the RS signal. However, if we exclude the RS signal, only the security of HI3 and HI4
400 classes would not be guaranteed. As such, these two classes of people should avoid to
401 work in such a noisy environment.

402 In the second approach, the idea was to quantify how much the protected thresholds of
403 the HI differed from the unprotected thresholds of the NH. Thus, a Wilcoxon rank-sum
404 test for unmatched data was used to check whether the protected thresholds of the HI
405 classes significantly exceeded the unprotected thresholds of the NH majored by 3 dB
406 ($T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$). This difference of 3 dB has been chosen as it seems
407 rather small compared to the intrinsic variations of signal levels that are typically
408 observed in the field, notably because of the variations of the positions of the workers
409 respective to the location(s) of the warning signal device(s). The results of these new
410 statistical analyses are shown in Table 6.

411
412 Table 6: Statistical comparison (p) between protected thresholds of the HI and
413 unprotected thresholds of the NH majored by 3 dB ($T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$).
414 Values in bold, italic and with the “*” sign indicate a statistically significant difference
415 ($p < 0.05$).
416

417
418 From Table 6, it appears that the protected thresholds of HI1 and HI2 classes are not
419 significantly different than the unprotected thresholds of NH majored by 3 dB for the
420 seven warning signals tested, including the RS signal.

421
422 Finally, if we do not consider the RS signal because it is not suitable as a warning signal,
423 the two approaches lead to the same conclusion: the security is assured for the HI1 and
424 HI2 classes (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear $< 30 \text{ dB}$)
425 but not for the HI3 and HI4 classes.

426 This limit of PTA $< 30 \text{ dB}$ to avoid the impediments due to wearing HPDs is consistent
427 with the results of Lazarus [5]. However, it is worth noting that the proposed limit of PTA
428 $< 30 \text{ dB}$ is more restrictive than the criterion proposed in the USA by the Federal Railroad
429 Administration [23] which tolerates a PTA in the better ear of up to 40 dB.
430

431 **6. Conclusion**

432 In this study, the influence of wearing HPDs on the detection of warning signals in noise
433 was evaluated by comparisons of the masked thresholds measured with and without
434 wearing HPDs, for seven warning signals. The results show that wearing the HPDs
435 improves the audibility of warning signals in noise for NH listeners whereas it tends to
436 impede the audibility for HI listeners. Moreover, the impediments greatly depend on the
437 warning signal acoustical characteristics.

438 In order to ensure the security of the workers, the RS signal should not be taken into
439 account because it is not suitable as a warning signal [22]. In these conditions, it was
440 found that the security is assured for the HI1 and HI2 classes wearing any of the two
441 HPDs tested (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear $< 30 \text{ dB}$)
442 but not for the HI3 and HI4 classes.

443 Future studies should focus on the influence of wearing a HPD on other aspects such as
444 the required signal levels to identify the signal (as in the study by Lazarus [5]), the
445 localization of the warning signal and the perceived urgency of the warning signal [18]
446 which have not been studied here. Furthermore, whatever the current experiment
447 attempts to mimic a realistic environmental situation, all the situations that may occur in
448 the field have not been studied in the laboratory and the current results could not be
449 generalized. As a consequence, the current results cannot guarantee that the signals will
450 always be heard in practice and extra caution is required when using HPDs in the field.
451 Further listening tests as presented in Standard N° ISO 7731:2003 (Annex C) while
452 wearing the HPDs could be useful to provide additional information.

453 Despite these limitations and based on the results from this study, some general
454 recommendations can be addressed concerning the wearing of HPDs by HI listeners.

455 First of all, the HPD must be chosen so as not to overprotect the wearers. Indeed, the
456 higher the attenuation values, the higher the potential impediments due to the absolute
457 thresholds [4]. In accordance with Standard N° EN458 [13], the HPD must be chosen to
458 meet a **A-weighted** daily exposure level under the HPD between 70 and 75 dB.

459 Second, protectors with a flat/uniform attenuation profile must be privileged so as to limit
460 the impediment due to frequency masking [4]. Because most passive HPDs show little
461 attenuation values in the low-frequency range, special caution must be taken when the
462 background noises dominate in low frequency and active noise reduction (ANR) HPDs
463 [24] should be privileged in this case as they bring an additional active attenuation in low
464 frequency.

465 Concerning the sound design of warning signals, it is clear that warning signals with
466 dominant components in low-frequency must be preferred since they are less affected
467 by the wearing of HPDs, especially for hearing impaired listeners. Conversely, signals
468 with not enough energy in low frequency must be avoided since their audibility is more
469 adversely affected when using HPDs. This recommendation is consistent with the
470 requirement from Standard N° ISO 7731 to use signals that have enough energy below
471 1500 Hz when people wear HPDs or when they suffer from hearing impairment.

472

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476

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478

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1 **Experimental assessment of the effect of wearing hearing protectors on the** 2 **audibility of railway warning signals for normal hearing and hearing impaired** 3 **listeners** 4

5 **1. Introduction**

6 In noisy workplaces, acoustic warning signals are often used to promptly alert workers
7 of a dangerous situation. To guarantee the workers' safety, the audibility of warning
8 signals is of paramount importance. This audibility can however be impeded in
9 practice by the wearing of hearing protection devices (HPDs), especially for hearing
10 impaired workers [1].

11 Nevertheless, according to Directive 2003/10/EC [2], HPDs should be worn when **A-**
12 **weighted** daily noise exposure levels exceed 80 dB to avoid hearing impairment and,
13 over 85 dB, this becomes strictly imperative.

14 In a previous study [3], the effect of wearing HPDs on the audibility of railroad warning
15 signals was evaluated on normal hearing (NH) listeners from masked threshold
16 measurements performed both with and without wearing the HPDs. The results of this
17 former study evidenced that wearing the HPDs generally improved the audibility (as
18 compared to no HPD) for warning signals having a sufficient amount of energy in the
19 low-frequency range ($f < 1500$ Hz). On the contrary, for hearing-impaired (HI) listeners,
20 other previous studies suggest that HPDs can have a more detrimental effect [4, 5, 6, 7].
21 This is probably due to a joint effect of elevated absolute thresholds and broadened
22 auditory filters. This result remains to be confirmed with some specific warning signals
23 and the present study was therefore dedicated to evaluate the effect of wearing HPDs
24 on the detection of railroad warning signals for both NH and HI listeners.

25 **2. Expected effects of wearing HPDs**

26 The influence of wearing HPDs on the audibility of a warning signal is traditionally
27 assessed by evaluating the masked detection threshold of the signal both with and
28 without wearing the HPD [6]. The masked detection threshold is defined as the sound
29 level of a signal at which this signal embedded in noise is just detectable. When the
30 masked detection threshold with the HPD is smaller (respectively larger) than the
31 masked threshold without the HPD, wearing the HPD improves (respectively impedes)
32 the audibility of the signal.

33
34 As described in the literature, two phenomena may explain an impediment of the
35 audibility when wearing HPDs; while a third phenomenon could explain an improvement
36 of the audibility [3, 6].

37
38 First, detection may be impeded because the sound attenuation provided by the HPD
39 leads the warning signal levels to be below the absolute thresholds of the workers; so
40 that the signal cannot be heard anymore [4]. For normal hearing workers, this over-
41 protection effect might only appear for low to moderate noise levels in which the wearing
42 of HPDs is not required. However, for hearing impaired workers, this over-protection
43 effect may extend to much higher levels, especially in high frequency bands where
44 absolute thresholds are usually higher [8, 9] and HPD sound attenuations are usually
45 also larger.

46
47 Second, detection may be impeded by an increase of the upward spread of masking [4]
48 when the HPD is worn. An increase of the upward spread of masking mostly happens
49 when a low-frequency noise is combined with a HPD having smaller sound attenuation
50 values in the low frequency range than in the high-frequency range (which is the case
51 for most HPDs). In such a configuration, the masking of the higher frequency bands by

52 the lower frequency bands is only slightly modified by the HPD due to its rather reduced
53 sound attenuation values in the low frequency range. Moreover, the high-frequency
54 components of the warning signal are strongly attenuated by the HPD and the potential
55 masking effect of the noise is enhanced accordingly. Since HI listeners usually exhibit
56 broadened auditory filters [10, 11, 12], their upward spread of masking is increased
57 compared to NH listeners. This could then contribute to a larger detrimental effect of the
58 HPDs on the audibility for HI listeners. To avoid this detrimental effect, Standard No. EN
59 458:2016 [13] recommends the use of HPDs with ‘flat/uniform’ sound attenuation,
60 defined as HPDs with high frequency (H) minus low-frequency (L) sound attenuation
61 values less than or equal to 9 dB. This recommendation of ‘flat/uniform’ attenuation might
62 be particularly important for HI listeners because they are more affected by steeply
63 sloped attenuation functions than NH listeners [4]. For example, Giguère and Berger [4]
64 suggested that the attenuation slope should not exceed 6-7 dB/octave for mild hearing
65 loss and 3-4 dB/octave for moderate to severe high frequency hearing loss in order to
66 minimize the adverse effects of HPDs on the speech frequency range.
67 Besides, as part of the German criteria proposed by Liedtke in 2009 [14], the AIP
68 criterion¹ states that a HPD is suitable when the slope of the linear regression of mean
69 values of sound attenuation (obtained according to Standard No. ISO 4869-1:2018 [15])
70 for 125–4000 Hz is less than 3.6 dB/octave.

71
72 Third, HPDs can also improve the detection of warning signals in noise [6]. This
73 improvement would then be related to the non-linear growth of masking effects when
74 noise levels increase (see Moore [16] and Moore’s method in Standard No. ANSI
75 S3.4:2007 [17]). When wearing a HPD, the reduced noise levels at the ear increase
76 frequency selectivity (sharpened auditory filters) and consequently reduce masking,
77 resulting in lower masked thresholds [6].

78
79 Even though these three phenomena are well described in the literature, the influence of
80 wearing HPDs appears to depend on several factors such as the relative spectral
81 distributions of the noise and the warning signal, the sound attenuation of the HPD and
82 the hearing status of the subjects (both absolute thresholds and frequency selectivity).
83 Altogether, this makes the effect of wearing HPDs unpredictable and the experimental
84 results may sometimes appear contradictory (see, Lazarus [5] for an extensive review).

85 **3. Objective and methods**

86 The aim of this study was then to evaluate the effect of wearing HPDs on the audibility
87 of railroad warning signals for both NH and HI listeners. The methods involved three
88 main steps: (1) the choice of the warning signals and background noises to be tested,
89 (2) the measurement of the masked thresholds with and without HPDs and (3) the choice
90 of the statistical tests used to compare the masked thresholds with and without HPDs.
91 These three steps are further detailed in the next three sections. Next, from the results
92 of the statistical analyses, a criterion based on the absolute thresholds is then proposed
93 in order to guarantee the security of HI workers when wearing HPDs.
94

1 AIP stands for “Audibility, speech Intelligibility or Perception of informative operating
sound ”

95 **3.1. Warning signals and background noises**

96 To better match a realistic configuration, all the warning signals and background noises
97 used in the experiment were recorded in the field, close to the ears of a worker located
98 at his usual working area. Time recordings were performed using a calibrated class 1
99 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of
100 48 kHz. Seven warning signals daily used in the French railroad environment were
101 tested. They were chosen among others to get a diversity of time and frequency
102 characteristics (see Table 1). All but one have a harmonic structure (i.e., they are
103 composed of a fundamental frequency f_0 and of multiples of f_0). On the contrary, the
104 remaining RS signal is composed of two pure tones with no harmonic relationship.
105 All but two (DAPR and GSM) signals are stationary. DAPR and GSM consisted in an
106 alternation of two tones with high and low fundamental frequencies (see Table 1). The
107 first four signals in Table 1 are used to warn track workers from an incoming train. The
108 last three signals are used to inform train drivers of an event and require an action from
109 them (like pressing or releasing a driving component).

110
111 Table 1: Temporal and spectral characteristics of the warning signals.

112
113
114 All track workers' signals were tested in a ballast plough background noise whereas all
115 train drivers' signals were tested in the background noise generated by a railway vehicle
116 at maximal speed. The third-octave spectra of both background noises are shown in
117 Figure 1. These two background noises were chosen because much of their energy is
118 distributed in the low-frequency range ($f < 1000$ Hz). Such noises should then have a
119 larger potential masking effect [5].

120
121
122 Figure 1: Third-octave band spectra of background noises. Ballast plough noise (—);
123 railway vehicle noise (----).
124

125 **3.2. Masked threshold measurements**

126 The masked thresholds were measured using a two-interval, two-alternative forced
127 choice (2I-2AFC) procedure. The sound intervals (one containing only the background
128 noise, the other containing both the background noise and the warning signal) were
129 successively presented in random order. The listener's task was then to indicate the
130 interval with the warning signal. Each interval consisted in a 500 ms burst of noise and
131 the two intervals were separated by a 300 ms silent gap. The warning signal was 300
132 ms long and was temporally centered in the middle of one burst of noise (i.e. in the middle
133 of one interval). The A-weighted background noises level was constant and equal to 86
134 dB. At the beginning of the measurement procedure, the A-weighted level of the warning
135 signals was also set at 86 dB. This level varied during the measurement procedure
136 according to a "2 Down – 1 Up" adaptive rule to target a detection threshold
137 corresponding to 70.7% of detection [18]. The level of the signal first varied by steps of
138 5 dB. After three reversals, the variation step was reduced to 3 dB. After two additional
139 reversals, the step reached its final value of 1 dB. Once the last step of 1 dB was reached,
140 the test continued until four additional reversals were obtained. The masked threshold
141 value was then computed as the mean of these four last reversals.
142

143 **3.3. Statistical analyses**

144 The listeners were grouped in five different hearing classes depending on their absolute
145 thresholds values. From the measured masked thresholds obtained for each hearing
146 class and each HPD configuration (no HPD, earplugs, earmuffs), Shapiro–Wilk tests [19]
147 were first performed to evaluate the normality of the threshold distributions. Since the
148 normality assumption was not always true (i.e. $p < 0.1$), Wilcoxon rank tests [20] were
149 therefore performed (instead of Student's t tests which require a normal distribution of
150 the data) to compare the masked thresholds of HI listeners with those of NH listeners.
151 Next, Wilcoxon matched-pairs signed-rank tests were applied for each hearing class
152 upon the differences between protected and unprotected thresholds in order to better
153 characterize the beneficial or detrimental effect of HPD upon detection.

154 **4. Psychoacoustic experiments**

155 **4.1. Experimental set-up**

156 The psychoacoustic tests took place in a sound-proof room (rough dimensions $w \times d \times h =$
157 $5.4 \text{ m} \times 5.9 \text{ m} \times 2.9 \text{ m}$) treated in absorption (reverberation time of 0.42 s).
158 The listener was sat 2.6 m in front of one loudspeaker (KH 120A by Neumann, Germany)
159 that played the warning signals. The background noises were played by two other
160 loudspeakers (LSR6332 by JBL, USA) driven by a power amplifier (XLS 402 by Crown,
161 USA). The positions and orientations of these two loudspeakers were experimentally
162 determined to get a uniform sound field around the listener's head.
163 The uniformity of the sound field has been accurately controlled with acoustic
164 measurements performed at the center of an anticipated head and at six positions
165 situated 15 cm from the center (right, left, front, rear, up, down). The discrepancies
166 between each of these six positions and the center, for the two background noises used
167 in the experiment (played by the two LSR6332 speakers) and for a pink noise played on
168 the KH 120A loudspeaker, never exceeded 3 dB in 1/3 octave bands from 80 to 12500
169 Hz.
170 All audio signals were calibrated before each test session with a microphone located at
171 the same position than the center of the participant's head. The calibration consisted of
172 adjusting the gain of each audio signal (background noises and warning signals) to set
173 the **A-weighted** background noise level and the **A-weighted** warning signal level equal to
174 86 dB.
175

176 **4.2. Subjects**

177 Before their participation, subjects were first informed of the types of tests they were
178 going to take part in and of the anonymization process of the collected data. They were
179 then offered the opportunity to provide their informed consent.
180 Eighty people (25 females, 55 males) aged from 18 to 81 (mean 51.6 years, standard
181 deviation 15.3 years) participated to the experiment. Fifty-three people were SNCF
182 workers who volunteered to take part into the experiment during work-time. Twenty-
183 seven additional participants were recruited and paid a hourly-wage for their
184 participation. The participants' absolute hearing thresholds were measured performing a
185 pure-tone audiometry at the 11 standard audiometric frequencies from 125 to 8000 Hz
186 (see Figure 2). The participants were then distributed into five different hearing classes
187 according to their absolute thresholds. The participants from the first class were
188 considered as normal hearing (NH) listeners and had absolute thresholds below 20 dB
189 hearing level (HL) from 125 to 8000 Hz on both ears. Eighteen participants were
190 considered as NH listeners. The remaining participants were distributed into four

191 additional classes depending of their average absolute threshold at 500, 1000 and 2000
192 Hz on the best ear, noted PTA (for Pure-Tone Average) hereafter **and expressed in**
193 **hearing level dB**. Four classes of hearing impaired (HI) listeners were then considered:

- 194 - HI1: $10 < \text{PTA} \leq 20$ dB, 22 listeners
- 195 - HI2: $20 < \text{PTA} \leq 30$ dB, 18 listeners
- 196 - HI3: $30 < \text{PTA} \leq 40$ dB, 14 listeners
- 197 - HI4: $\text{PTA} > 40$ dB, 8 listeners.

198
199
200
201 Figure 2: Mean absolute thresholds of the five hearing classes (**expressed in hearing**
202 **level dB**). From top to bottom: NH (\cdot); HI1 (\circ); HI2 ($*$); HI3 ($+$); HI4 (\times).
203

204 Figure 2 shows the mean absolute thresholds of the five hearing classes. Additionally,
205 Table 2 provides the mean ages for each hearing class. For the HI classes, the increase
206 of absolute thresholds as a function of frequency is typical of age-related hearing loss
207 [8].
208

209 Table 2: Mean ages and *SD* for the 5 hearing classes
210

211 **4.3. Hearing protectors**

212 Two types of passive HPDs were tested:

- 213 - Earplugs: silicon custom-molded earplugs from ELACIN, France (model
214 Clearsound with an RC15 acoustic filter, single number rating (SNR) =17 dB)
- 215 - Earmuffs from Howard Leight by Honeywell (model Clarity C1, SNR = 25 dB).

216 Figure 3 shows the sound attenuation values provided by the manufacturers according
217 to Standard No. ISO 4869-1:2018 [15]. These two HPD models were chosen because
218 their sound attenuation profiles are relatively uniform as a function of frequency. The
219 slope of the linear regression of mean values of sound attenuation from 125 up to 4000
220 Hz is of 2.7 dB/oct for the earplugs and of 1.9 dB/oct for the earmuffs. As a consequence,
221 both HPDs fulfill the AIP criterion proposed by Liedtke [14] (with a slope lower than 3.60
222 dB/octave) along with the recommendation by Giguère and Berger [4] for moderate to
223 severe high frequency hearing loss (with a slope lower than 3-4 dB/octave).
224
225

226 Figure 3: Mean sound attenuation values provided by the manufacturers for the two
227 HPDs. Note: Error bars designate + 1 *SD* (earplugs) and – 1 *SD* (earmuffs).
228
229

230 **4.4. Test procedure**

231 For masked threshold measurements, listeners were first asked to listen to the 7 warning
232 signals alone (i.e. without any background noise). They were then trained on how to put
233 on the HPDs and performed at least three masked threshold measurements for practice.
234 The presentation order of experimental conditions (combination of warning signals and
235 HPDs configurations) was randomized for each listener. Each condition was repeated
236 three times and the three masked thresholds values were then averaged. However, if
237 the standard deviation of the masked thresholds on these three measurements
238 exceeded 3 dB, a fourth measurement was performed and the threshold was computed
239 as the average of the three nearest values. Thus each listener performed a minimum of
240 63 threshold measurements (7 alarms \times 3 configurations of HPD \times 3 repetitions)
241 distributed into 6 sessions of 10 or 11 measurements (the 6 sessions were distributed on

242 several days). The duration of one session typically varied between 20 and 30 minutes
243 leading to about 2,5 hours of testing for each participant.

244 5. Results and discussion

245 5.1. Masked thresholds measurements

246 Figure 4 shows the masked thresholds without HPD, plot as box and
247 whisker², independently for the five hearing classes and for the 7 warning signals. It
248 appears that the differences on the medians between the HI classes and the NH class
249 never exceed 10 dB and the difference of the medians between HI4 and NH averaged
250 across alarms is equal to 4.9 dB. Moreover, these differences greatly depend on the
251 warning signal considered.

252 Wilcoxon rank-sum tests for unmatched data were applied to these results in order to
253 estimate the effect of hearing impairment. The results of these statistical analyses,
254 presented in Table 3, indicate no significant differences ($p > 0.05$) between the HI classes
255 and the NH class for the signals AUTOPROVA and RS; whereas the differences are
256 significant ($p < 0.05$) between at least one HI class and the NH class for the five other
257 signals.

258
259

260 Figure 4: Masked thresholds without HPDs for the seven warning signals. For each
261 warning signal, the five box and whisker plots correspond to the five hearing classes
262 considered, from the NH class most to the left to the HI4 class most to the right.

263
264

265 Table 3: Masked threshold without HPDs (see Figure 4). Statistical results (p) of the
266 comparisons between the HI classes and the NH class. Values in bold, italic and with
267 the “*” sign indicate a statistically significant difference ($p < 0.05$).

268
269

270 Figures 5 and 6 show the masked thresholds with HPDs independently for the five
271 hearing classes and for the 7 warning signals. Figure 5 shows the results with the
272 earplugs and Figure 6 with the earmuffs.

273 The differences on the medians between the HI4 and the NH averaged across alarms
274 are respectively 10.1 dB and 11 dB for the earplugs and the earmuffs. Hence, these
275 differences are larger than the average difference without HPDs (4.9 dB).

276
277

278 This larger effect of hearing impairment when wearing HPDs is confirmed by the results
279 of the statistical analysis (Wilcoxon rank-sum tests for unmatched data) presented in
280 Table 4. In fact, significant effects of hearing impairment are found for all but one warning
281 signal (VACMA). For all the other warning signals, some HI groups have significant
282 higher thresholds than the NH group. Moreover, it seems from Table 4 that the effect of
283 hearing impairment increases when increasing the degree of hearing loss. Except for the
284 VACMA warning signal, the detection performances of the HI3 and HI4 groups are
285 always significantly poorer than for the NH group. Besides, the significance of the
differences between HI and NH listeners are very similar for the two HPDs considered

2 On each box, the central mark indicates the median, and the bottom and top edges of the box (of numerical values q_1 and q_3 , respectively) indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. The data points are drawn as outliers if they are greater than $q_3 + 1.5 \times (q_3 - q_1)$ or less than $q_1 - 1.5 \times (q_3 - q_1)$.

286 (earplugs and earmuffs).

287

288

289 Figure 5: Masked thresholds with earplugs for the seven warning signals. For each
290 warning signal, the five box and whisker plots correspond to the five hearing classes
291 considered, from the NH class most to the left to the HI4 class most to the right.

292

293

294 Figure 6: Masked thresholds with earmuffs for the seven warning signals. For each
295 warning signal, the five box and whisker plots correspond to the five hearing classes
296 considered, from the NH class most to the left to the HI4 class most to the right.

297

298 Table 4: Masked threshold with earplugs and earmuffs (see Figures 5 and 6). Statistical
299 results (p) of the comparisons between the HI classes and the NH class. Values in
300 bold, italic and with the “*” sign indicate a statistically significant difference ($p < 0.05$).

301

302

303 In summary, when no HPDs are worn, the differences between the masked thresholds
304 of the HI classes and those of the NH class are relatively small and are statistically
305 significant only for 4 out of the 7 signals tested. With HPDs, the differences between HI
306 and NH increase and become significant for all the warning signals except the VACMA
307 signal. The reason why there is no difference between HI and NH for the VACMA signal
308 is most certainly due to the fact that its audibility is governed by a dominant component
309 in low-frequency ($f_0=334$ Hz) that is not or little affected by the two phenomena leading
310 to an impediment of the detection (see section 2). Moreover, both HPDs (earplugs and
311 earmuffs) lead to the same pattern of results.

312

313 **5.2. Differences between protected and unprotected thresholds**

314 To better evaluate the effect of wearing HPDs on the detection of warning signals, the
315 differences between protected and unprotected thresholds have been computed. A
316 positive difference value indicates that the HPD impedes the detection (as compared to
317 no HPD); conversely a negative value corresponds to an improvement of the detection.
318 Figures 7 and 8 show these differences for the earplugs and the earmuffs, respectively.

319

320

321

322 Figure 7: Differences between thresholds with and without earplugs for the seven
323 warning signals. For each warning signal, the five box and whisker plots correspond to
324 the five hearing classes considered, from the NH class most to the left to the HI4 class
325 most to the right.

326

327

328 Figure 8: Differences between thresholds with and without earmuffs for the seven
329 warning signals. For each warning signal, the five box and whisker plots correspond to
330 the five hearing classes considered, from the NH class most to the left to the HI4 class
331 most to the right.

332

333

334 Additionally, Wilcoxon matched-pairs signed-rank tests were performed to evaluate
335 whether these differences were statistically positive or negative. Table 5 summarizes the

336 statistical results: an up arrow symbol³ “↑” designates a statistically significant
337 impediment ($p < 0.05$); a down arrow symbol “↓” symbol designates a statistically
338 significant improvement ($p < 0.05$) and no symbol designates no statistically significant
339 effect.

340
341

342 Table 5: Differences between protected and unprotected thresholds (see Figures 7 and
343 8). Statistical results of the significant improvements (“↓” symbol, $p < 0.05$) or
344 impediments (“↑” symbol, $p < 0.05$). No symbol indicates no statistically significant
345 difference ($p > 0.05$).

346
347

348 For NH listeners, it appears that wearing any of the two HPDs improves the detection for
349 all the warning signals (except VACMA). These improvements for NH listeners are
350 consistent with the results from previous studies [3, 5, 21]. For the VACMA signal, most
351 of the audibility is due to a dominant component in low-frequency ($f_0=334$ Hz). It can then
352 be hypothesized that no improvement is found due to the reduced attenuation values of
353 the HPDs around 300 Hz (which lead, as compared to no HPD, to a low reduction of the
354 frequency masking phenomena, see section 2).

355

356 For HI listeners, detection improves for less and less warning signals when the absolute
357 thresholds (i.e. the hearing loss) increase. As such, for the HI1 class, detection is
358 improved for both HPDs for three warning signals (DAPR, STDIZIER and GSM),
359 whereas for the HI3 and HI4 classes, no statistically significant improvement is found
360 whatever the warning signal and the HPD considered.

361 Concerning the impediments, the RS warning signal is by far the most impeded signal:
362 the differences between protected and unprotected thresholds reach around 10 dB on
363 the medians for the HI4 class and statistically significant differences are found for HI2,
364 HI3 and HI4 classes for earplugs and for all the HI classes for the earmuffs. This severe
365 impediment is most certainly due to the fact that the RS signal is made of two high-
366 frequency components (3430 and 4084 Hz). Indeed, over 3 kHz, both the absolute
367 thresholds values and the HPD attenuations are high (see Figures 2 and 3), leading to
368 an over-attenuation effect due to the absolute thresholds (as described in [4], see section
369 2). This signal is not in agreement with Standard No. ISO 7731:2003 [22], which
370 recommends to use two dominant components between 500 and 1500 Hz and highlights
371 that, when people wear HPDs or suffer from hearing loss, the signal must have enough
372 energy below 1500 Hz. This signals should therefore be modified to increase its energy
373 in the low-frequency range ($f < 1500$ Hz) to be better detected.

374 Significant impediments are also found with earplugs for the warning signal GSM (HI4)
375 and with earmuffs for the warning signal AIGU for HI3 and HI4 classes.

376 It is worth noting that no statistically significant impediment is found whatever the hearing
377 class considered for the four remaining warning signals: PROVA, DAPR, STDIZIER and
378 VACMA. This can be explained by the fact that these signals have a dominant
379 fundamental frequency in low-frequency (between 334 and 660 Hz, see Table 1) that is
380 not or little affected neither by the absolute thresholds effect nor by the upward spread
381 of masking effect (see section 2). Hence these warning signals appear to be particularly
382 adapted to HI listeners.

383

³ The *up* arrow was chosen to indicate a threshold *elevation* when HPDs are worn (as compared to no HPD)

384

5.3. Towards a criterion for HI listeners wearing HPDs

385 The previous section has shown that wearing the HPDs improves the audibility for NH
386 listeners whereas it tends to impede the audibility for HI listeners. Moreover, the
387 impediments greatly depend on the signal considered.

388 In an attempt to propose a criterion based on the absolute thresholds of HI people that
389 guarantees their security when wearing HPDs, two approaches have been used.

390 In the first approach, it was simply considered that any significant impediment should be
391 avoided. From Table 5, the security of all HI classes could not be guaranteed because
392 of the RS signal. However, if we exclude the RS signal, only the security of HI3 and HI4
393 classes would not be guaranteed. As such, these two classes of people should avoid to
394 work in such a noisy environment.

395 In the second approach, the idea was to quantify how much the protected thresholds of
396 the HI differed from the unprotected thresholds of the NH. Thus, a Wilcoxon rank-sum
397 test for unmatched data was used to check whether the protected thresholds of the HI
398 classes significantly exceeded the unprotected thresholds of the NH majored by 3 dB
399 ($T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$). This difference of 3 dB has been chosen as it seems
400 rather small compared to the intrinsic variations of signal levels that are typically
401 observed in the field, notably because of the variations of the positions of the workers
402 respective to the location(s) of the warning signal device(s). The results of these new
403 statistical analyses are shown in Table 6.

404

405 Table 6: Statistical comparison (p) between protected thresholds of the HI and
406 unprotected thresholds of the NH majored by 3 dB ($T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$).

407 Values in bold, italic and with the "*" sign indicate a statistically significant difference
408 ($p < 0.05$).

409

410

411 From Table 6, it appears that the protected thresholds of HI1 and HI2 classes are not
412 significantly different than the unprotected thresholds of NH majored by 3 dB for the
413 seven warning signals tested, including the RS signal.

414

415 Finally, if we do not consider the RS signal because it is not suitable as a warning signal,
416 the two approaches lead to the same conclusion: the security is assured for the HI1 and
417 HI2 classes (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear $< 30 \text{ dB}$)
418 but not for the HI3 and HI4 classes.

419 This limit of PTA $< 30 \text{ dB}$ to avoid the impediments due to wearing HPDs is consistent
420 with the results of Lazarus [5]. However, it is worth noting that the proposed limit of PTA
421 $< 30 \text{ dB}$ is more restrictive than the criterion proposed in the USA by the Federal Railroad
422 Administration [23] which tolerates a PTA in the better ear of up to 40 dB.

423

424

6. Conclusion

425 In this study, the influence of wearing HPDs on the detection of warning signals in noise
426 was evaluated by comparisons of the masked thresholds measured with and without
427 wearing HPDs, for seven warning signals. The results show that wearing the HPDs
428 improves the audibility of warning signals in noise for NH listeners whereas it tends to
429 impede the audibility for HI listeners. Moreover, the impediments greatly depend on the
430 warning signal acoustical characteristics.

431 In order to ensure the security of the workers, the RS signal should not be taken into
432 account because it is not suitable as a warning signal [22]. In these conditions, it was
433 found that the security is assured for the HI1 and HI2 classes wearing any of the two
434 HPDs tested (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear $< 30 \text{ dB}$)
435 but not for the HI3 and HI4 classes.

436 Future studies should focus on the influence of wearing a HPD on other aspects such as
437 the required signal levels to identify the signal (as in the study by Lazarus [5]), the
438 localization of the warning signal and the perceived urgency of the warning signal [18]
439 which have not been studied here. Furthermore, whatever the current experiment
440 attempts to mimic a realistic environmental situation, all the situations that may occur in
441 the field have not been studied in the laboratory and the current results could not be
442 generalized. As a consequence, the current results cannot guarantee that the signals will
443 always be heard in practice and extra caution is required when using HPDs in the field.
444 Further listening tests as presented in Standard N° ISO 7731:2003 (Annex C) while
445 wearing the HPDs could be useful to provide additional information.
446 Despite these limitations and based on the results from this study, some general
447 recommendations can be addressed concerning the wearing of HPDs by HI listeners.
448 First of all, the HPD must be chosen so as not to overprotect the wearers. Indeed, the
449 higher the attenuation values, the higher the potential impediments due to the absolute
450 thresholds [4]. In accordance with Standard N° EN458 [13], the HPD must be chosen to
451 meet a **A-weighted** daily exposure level under the HPD between 70 and 75 dB.
452 Second, protectors with a flat/uniform attenuation profile must be privileged so as to limit
453 the impediment due to frequency masking [4]. Because most passive HPDs show little
454 attenuation values in the low-frequency range, special caution must be taken when the
455 background noises dominate in low frequency and active noise reduction (ANR) HPDs
456 [24] should be privileged in this case as they bring an additional active attenuation in low
457 frequency.
458 Concerning the sound design of warning signals, it is clear that warning signals with
459 dominant components in low-frequency must be preferred since they are less affected
460 by the wearing of HPDs, especially for hearing impaired listeners. Conversely, signals
461 with not enough energy in low frequency must be avoided since their audibility is more
462 adversely affected when using HPDs. This recommendation is consistent with the
463 requirement from Standard N° ISO 7731 to use signals that have enough energy below
464 1500 Hz when people wear HPDs or when they suffer from hearing impairment.

465
466 **Acknowledgements**
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Warning signal name	Temporal characteristics	Spectral characteristics	Frequency content
PROVA	Stationnary	Harmonic	$f_0 = 660$ Hz + 3 first harmonics. Most of the energy to the first and second harmonics
AIGU	Stationnary	Harmonic	$f_0 = 647$ Hz + many harmonics. Main components at 647, 1941 and 2588 Hz
DAPR	Two-tones (high-low)	High: harmonic	$f_0 = 656$ Hz + many harmonics with a flat energetic distribution up to 3000 Hz
		Low: harmonic	$f_0 = 427$ Hz + many harmonics with a flat energetic distribution up to 3000 Hz
STDIZIER	Stationnary	Harmonic	$f_0 = 358$ Hz + many harmonics. A loud component at 1432 Hz and a flat energetic distribution for the other components from 350 to 4000 Hz
GSM	Two-tones (high-low)	High: almost pure tone	$f_0 = 1800$ Hz (all other harmonic components are strongly attenuated)
		Low: almost pure tone	$f_0 = 1400$ Hz (all other harmonic components are strongly attenuated)
RS	Stationnary	Two inharmonic components	3430 Hz et 4084 Hz
VACMA	Stationnary	Harmonic	$f_0 = 334$ Hz + a few harmonics. Most of the energy at 334 and 1002 Hz

Hearing class	Mean age (years)	<i>SD</i> (years)
NH	36,9	11,4
HI1	50	8,6
HI2	55,2	17,6
HI3	62	14,1
HI4	58,6	12,7

Hearing class	Warning signal name						
	PROVA	AIGU	DAPR	STDIZIER	GSM	RS	VACMA
HI1	0,8172	0,0307*	0,0750	0,0750	0,0626	0,2479	0,0487*
HI2	0,9874	0,0018*	0,0130*	0,009*	0,0184*	0,1708	0,0967
HI3	0,4361	0,0004*	0,0093*	0,0015*	0,0022*	0,1335	0,0654
HI4	0,7180	0,0002*	0,0801	0,0211*	0,0157*	0,5977	0,0801

Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
HI1	0,2592	0,3624	0,0010*	0,0005*	0,0893	0,0004*	0,0232*	0,6934	0,1615	0,1313	0,0375*	0,0139*	0,2829	0,4226
HI2	0,0642	0,0517	0,0001*	0,0001*	0,0062*	0,0042*	0,0002*	0,0090*	0,0016*	0,0130*	0,0018*	0,0014*	0,4018	0,4765
HI3	0,0216*	0,0052*	0,0000*	0,0001*	0,0001*	0,0000*	0,0000*	0,0047*	0,0000*	0,0001*	0,0001*	0,0000*	0,0839	0,0654
HI4	0,0244*	0,0050*	0,0001*	0,0001*	0,0014*	0,0001*	0,0014*	0,0001*	0,0030*	0,0030*	0,0001*	0,0005*	0,1917	0,1566

Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
NH	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	-	-
HI1	-	↘	↘	-	↘	↘	↘	↘	↘	↘	-	↗	-	-
HI2	-	↘	-	-	↘	↘	-	↘	-	-	↗	↗	↘	-
HI3	-	-	-	↗	-	-	-	-	-	-	↗	↗	-	-
HI4	-	-	-	↗	-	-	-	-	↗	-	↗	↗	-	-

Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
HI1	0,9983	0,9999	0,8259	0,7808	0,9847	0,9983	0,9884	0,9996	0,9554	0,9996	0,9786	0,876	0,9377	0,7206
HI2	0,9777	0,9946	0,1	0,2482	0,9	0,8693	0,4185	0,8693	0,1921	0,8327	0,328	0,1651	0,9204	0,8247
HI3	0,8767	0,9748	0,0159*	0,0009*	0,1481	0,2654	0,0575	0,3879	0,0159*	0,0492*	0,0667	0,0058*	0,4025	0,207
HI4	0,4668	0,5552	0,0004*	0,0007*	0,0567	0,0355*	0,0314*	0,0355*	0,0042*	0,0067*	0,0025*	0,0162*	0,6615	0,1946

Figure 1

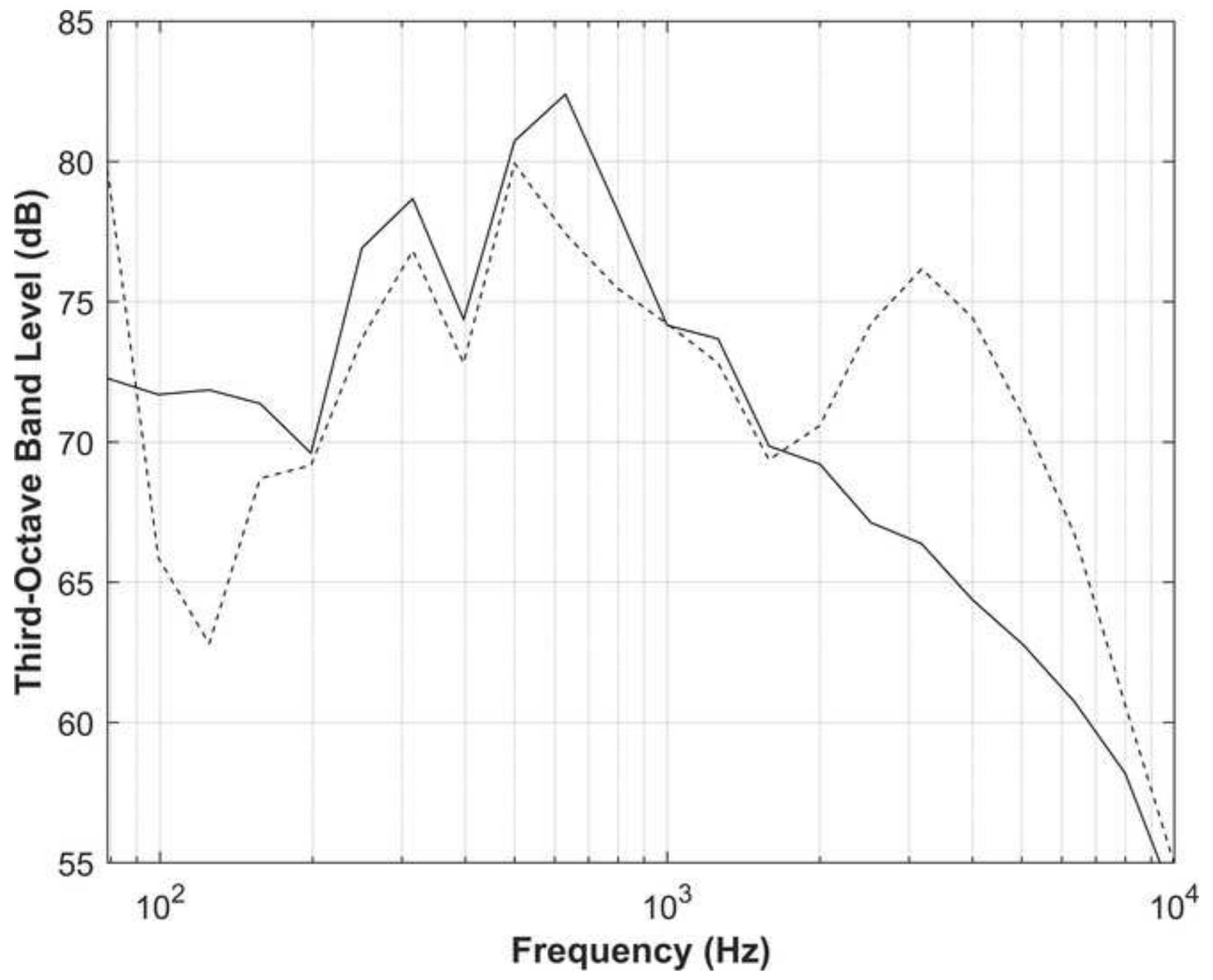


Figure 2

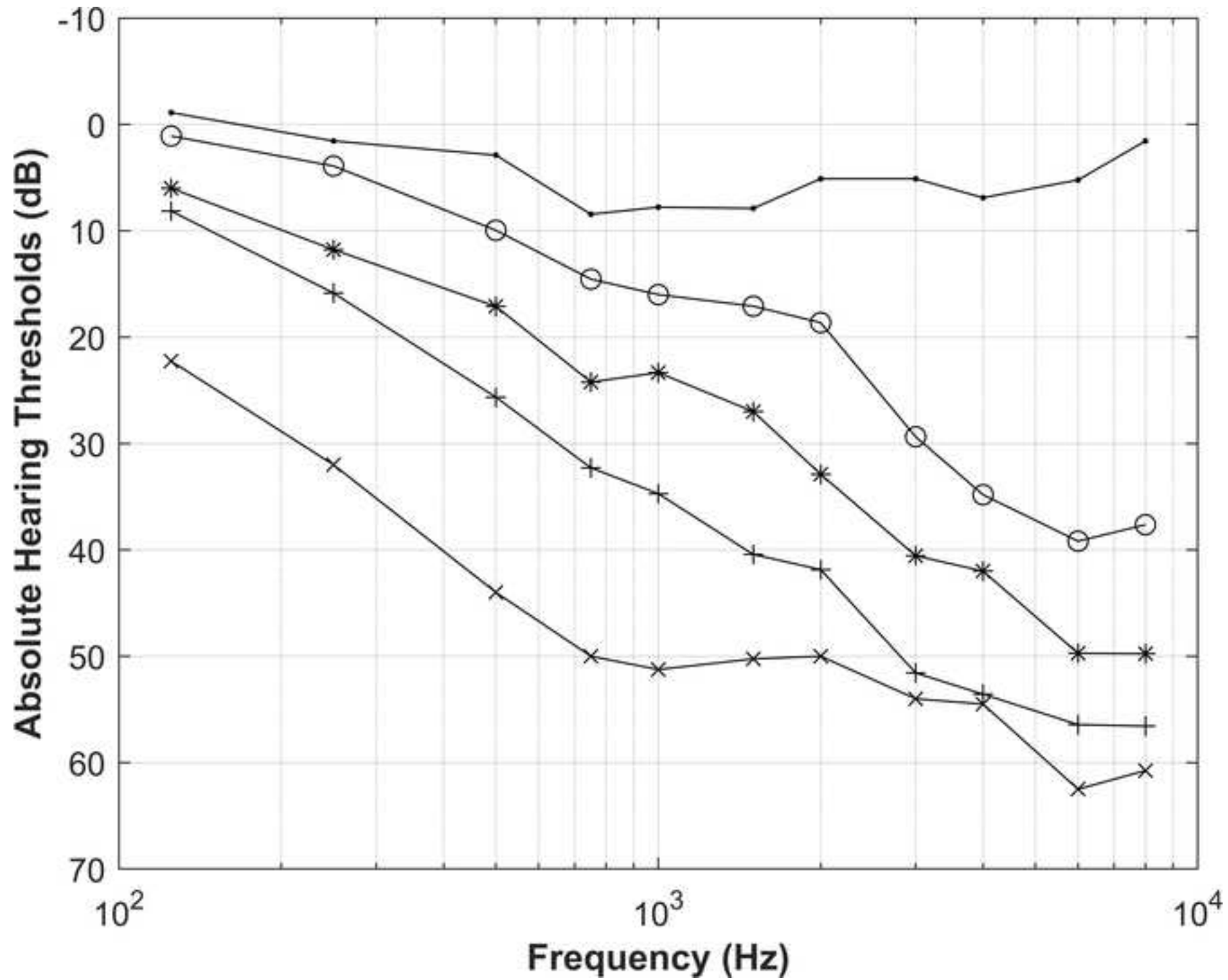


Figure 3

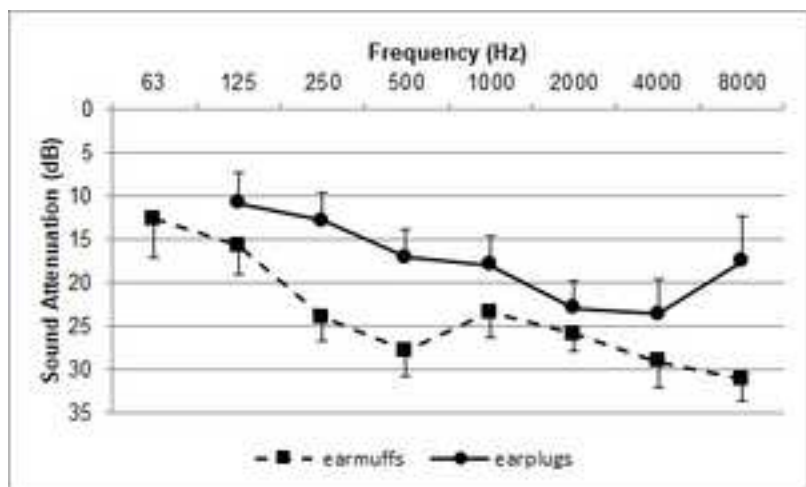


Figure 4

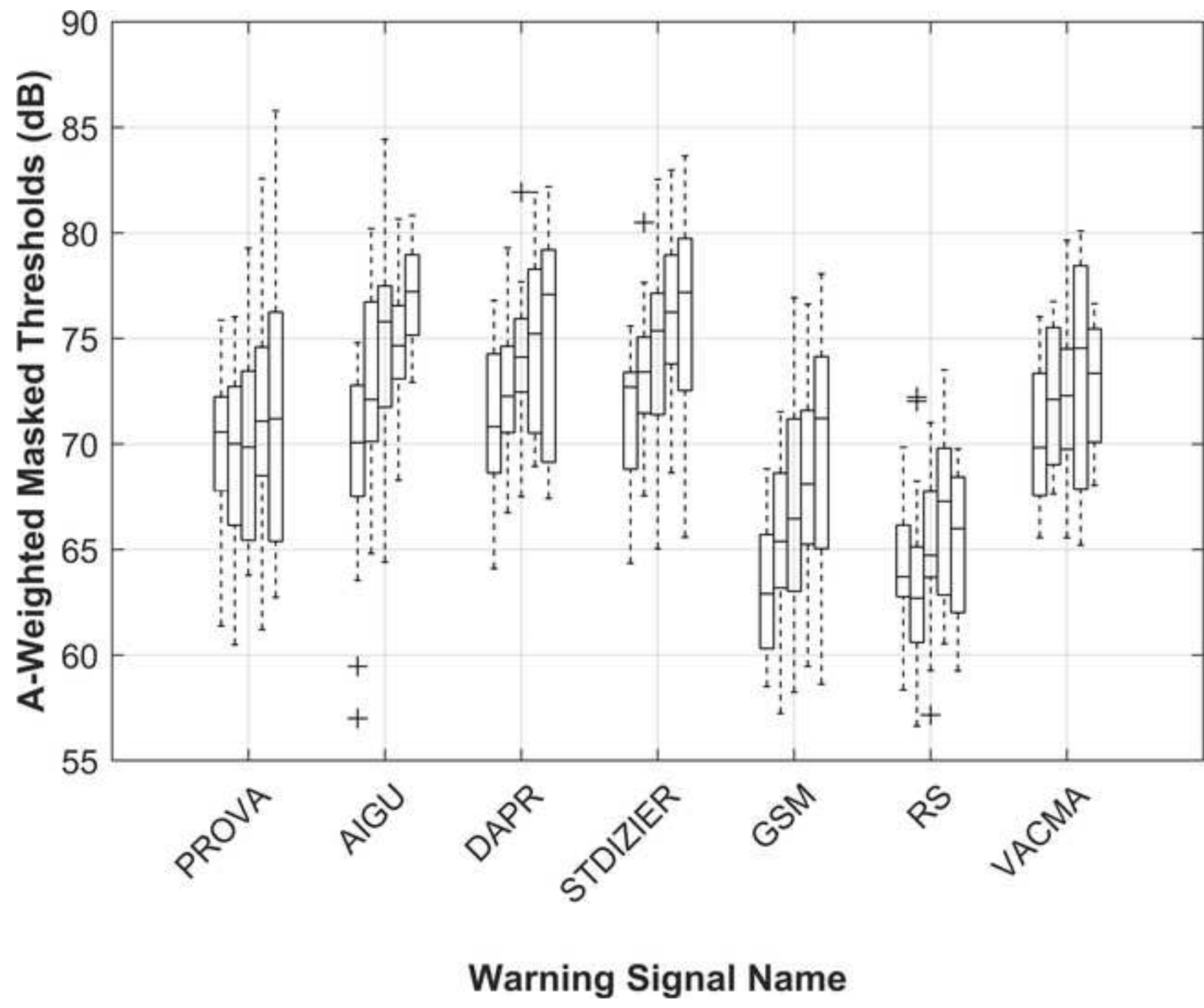


Figure 5

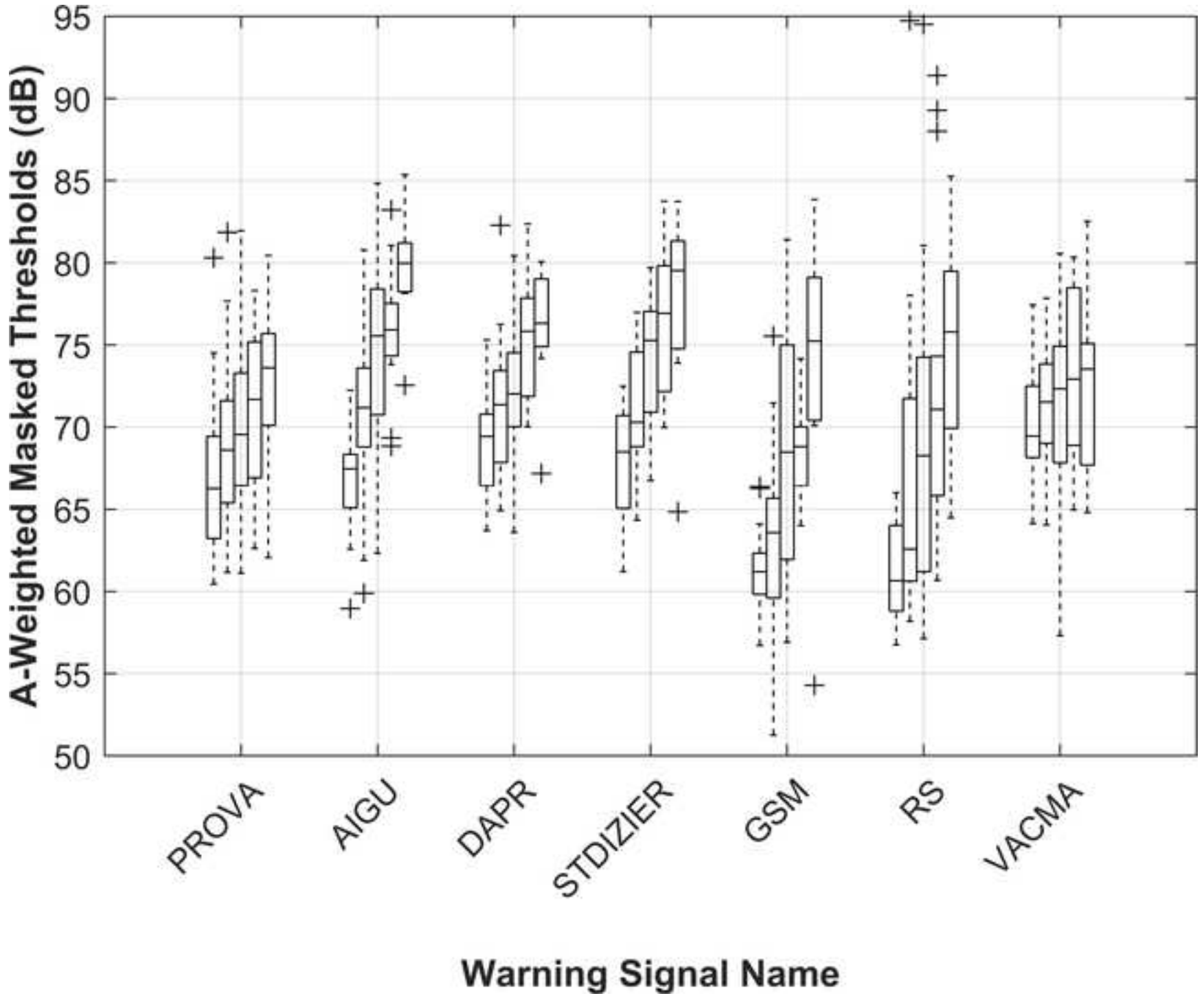


Figure 6

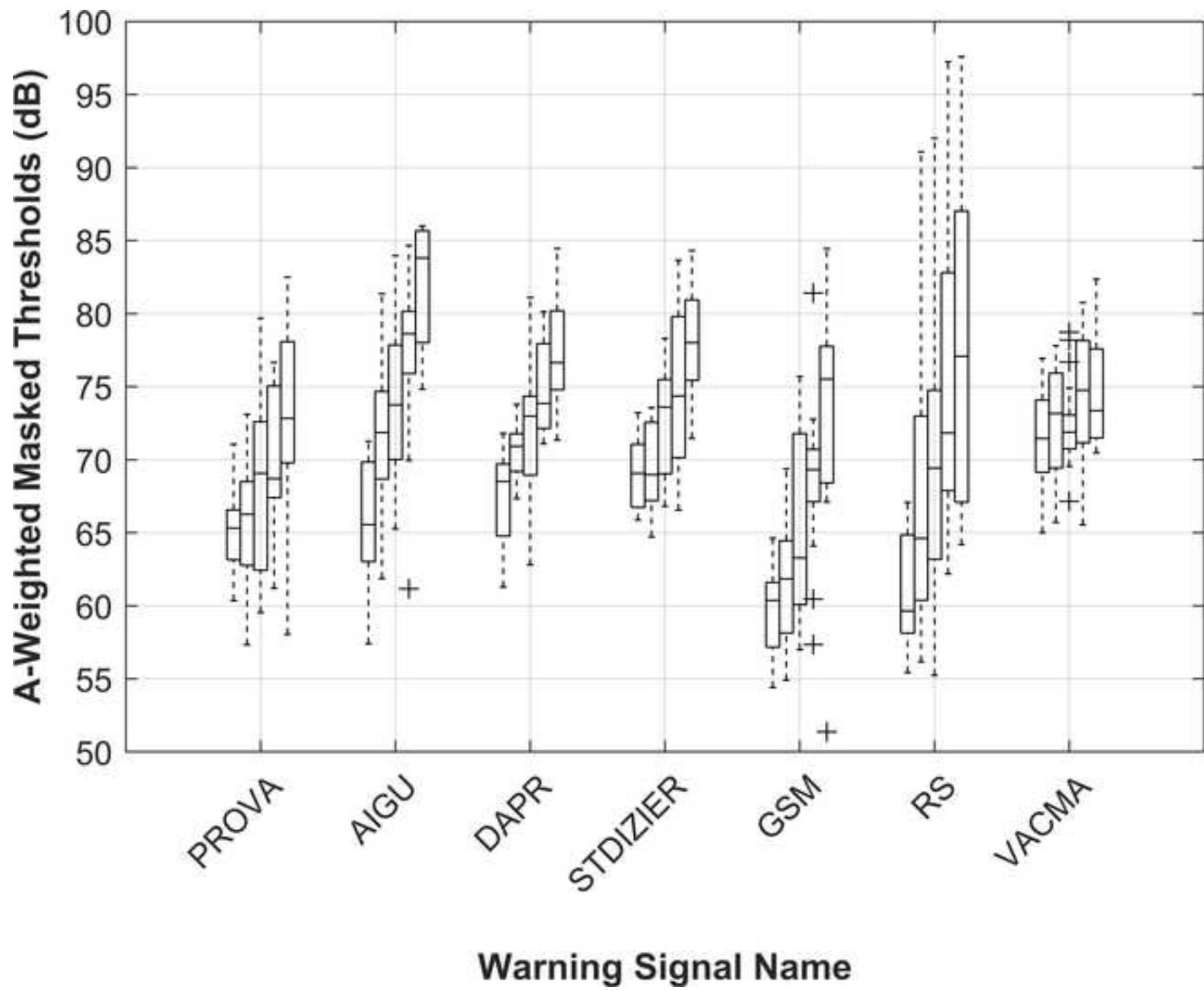


Figure 7

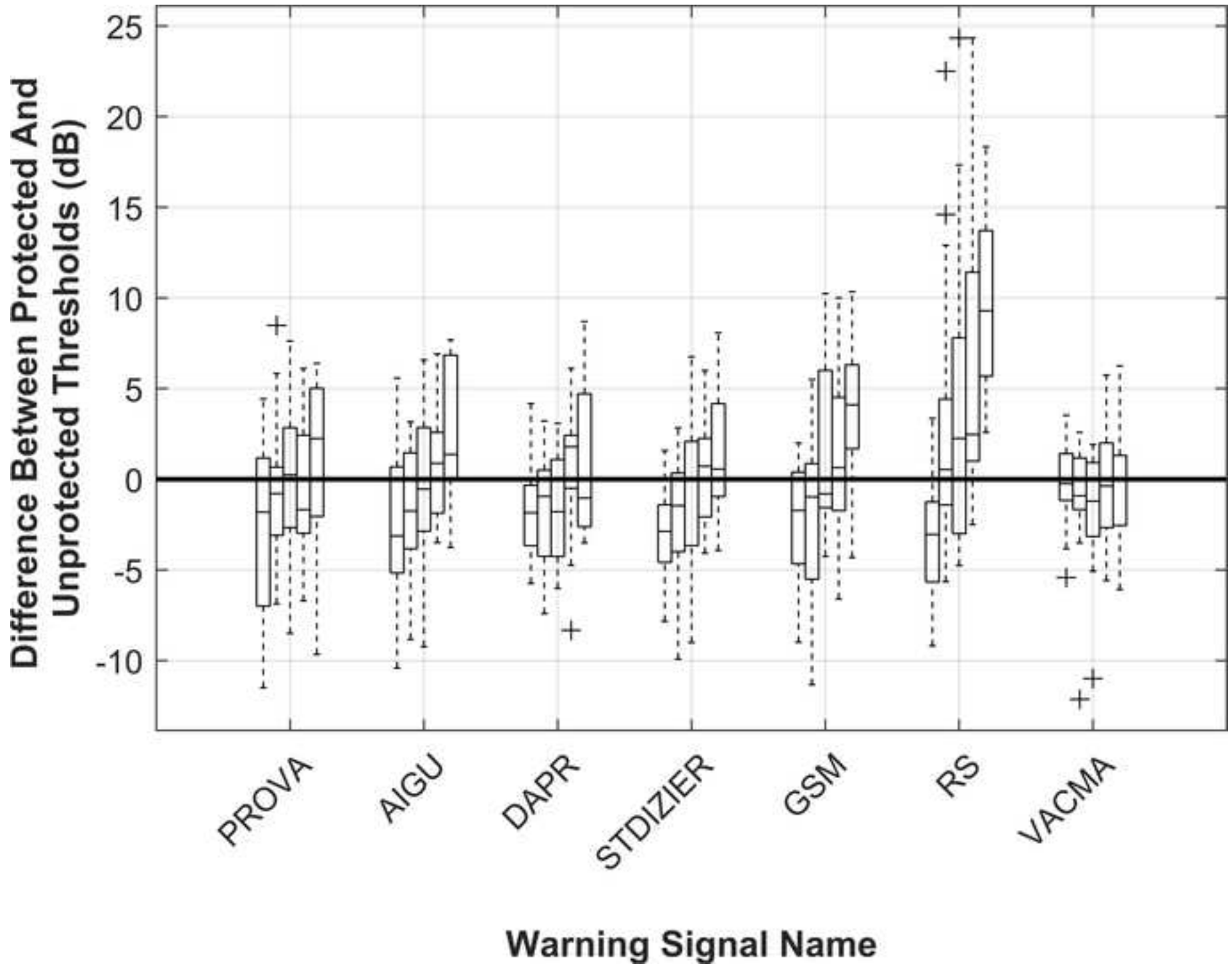
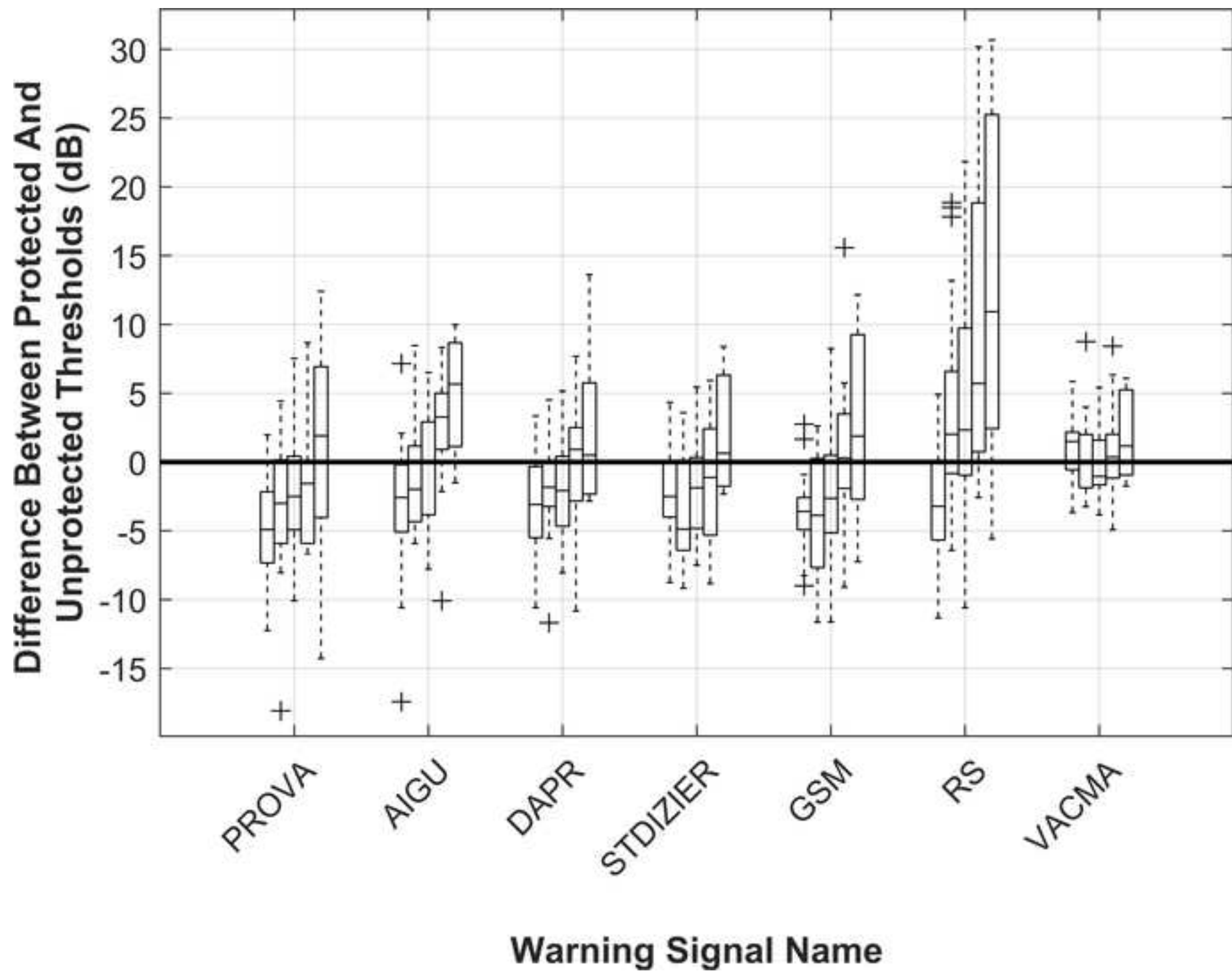


Figure 8



Reviewer #1: The article deals with issues important for security reasons. The manuscript is well prepared. The following comments can be made, which will further improve its quality:

1. The advantage of work is the use of actual recorded audio signals. Inquisitive readers would like to know how they were registered (what equipment was used, what technique was used, what were the registration parameters?).

The following sentence has been added:

“Time recordings were performed using a calibrated class 1 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of 48 kHz.”

2. The truth is that you can find many instances of writing units like "dBA" or "dB (A)" even in Directive 2003/10 / EC. This way of writing units is convenient e.g. in the interface of sound level meters. However, such notations should be avoided in a scientific article. The notation "dB" is acceptable, but if you need to include A-weighting information, write it in the parameter name, e.g. "LA", "LAeq" etc. The unit will then be "dB". These notations are defined in the relevant standards (ISO 9612). A similar situation applies to the phrase like "dB HL", where information about the hearing level should be included in the parameter name. Please take this into account in the manuscript and in the descriptions of the figure axes.

Relevant modifications have been made through the whole manuscript and figures.

3. Lines 55-56: "Since HI listeners usually exhibit broadened auditory filters..." - this is not obvious information to the reader. Please support this with references to literature.

The three following references have been added:

Moore, B.C.J. and B.R. Glasberg, *Formulae describing frequency selectivity as a function of frequency and level, and their use in calculating excitation patterns*. *Hear Res*, 1987. **28**: p. 209–225.

Leek, M.R. and V. Summers, *Auditory filter shapes of normal-hearing and hearing-impaired listeners in continuous broadband noise*. *The Journal of the Acoustical Society of America*, 1993. **94**(6): p. 3127-3137.

Glasberg, B.R. and B.C.J. Moore, *Derivation of auditory filter shapes from notched-noise data*. *Hearing Research*, 1990. **47**(1-2): p. 103-138.

Reviewer #2: Congratulations. Well done!